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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
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NAMRL TECHNICAL MEMORANDUM 92-3

**A COMPUTER PROGRAM TO
CALCULATE PLANEWAVE AVERAGE
SPECIFIC ABSORPTION RATE IN A
PROLATE SPHEROIDAL MODEL**

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13. ABSTRACT (Maximum 200 words) This report documents a computer program that was developed locally to compute the average specific absorption rate (SAR) for any prolate spheroidal target. It was developed using equation 5.10 from the Radiofrequency Radiation Dosimetry Handbook (4th ed). The program, which is IBM-compatible, is capable of calculating the SAR during microwave radiation exposure for all model sizes ranging from a small mouse to a large human. This procedure removes the restriction of using the Radiofrequency Radiation Dosimetry Handbook, which is limited to only a single or, in some cases, a few sizes of spheroid models.				
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SUMMARY PAGE

OVERVIEW

The average specific absorption rate (SAR) is often needed to corroborate a biological finding in a research project or to evaluate human exposure in an occupational or medical setting relative to safety standards. Safety standards (1) promulgate SAR as the metric of maximum permissible exposure. The measurement of SAR in a biological organism exposed to microwave radiation, however, can be a laborious, time-consuming, and sometimes perplexing task. We developed a computer program to compute the average SAR using Equation 5.10 from the Radiofrequency Radiation Dosimetry Handbook, 4th ed.(2). This report describes the computer program, graphical representations of data generated by the program, and methods used to obtain experimental SAR test data.

Acknowledgments

The authors wish to thank Mr. Alfred Thomas for his assistance in many facets of this project: constructing the monkey model bags, preparing the models for experimental testing, and aiding in the calorimetry experiments. In addition, HM2 Lee Buford, Mr. Alfred Thomas, and Mr. Robert Upchurch are gratefully acknowledged for their assistance in construction of the calorimeter, which was utilized to measure the specific absorption rates. Mrs. Peggy Tracy's assistance in correcting and typing the final manuscript is also greatly appreciated.

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INTRODUCTION

Laboratory scientists and radiation safety officers in an occupational setting are often required to denote the specific absorption rate (SAR) of a laboratory animal or man exposed to microwave radiation. In the first case, specifying the absorbed dose rate is necessary so that other scientists can replicate an experiment. In the second case, current safety standards (1,3) specify the maximum permissible SAR for occupational as well as general public exposure. Knowledge of the SAR that corresponds to a given field power density found in the occupational or public access areas can be helpful to the safety officer.

The average whole-body SAR can be determined empirically using several calorimetric methods. In the laboratory this usually involves exposing animal carcasses or animal models to microwaves and then measuring thermal changes with temperature probes or whole-body calorimeters (4,5). Recently, methods have been developed to measure SAR in a homogeneous man model in field settings with twin-well calorimeters (6). To determine the SAR, accurate thermal measurements are required that demand careful attention to sources of artifacts. In addition, twin-well calorimetry is a slow process that requires a pair of carcasses or models, which can be costly. These are difficult procedures in a controlled laboratory setting and even more arduous in a noncontrolled field location.

In recent years, a variety of analytical methods have been developed to estimate SAR (7,8). Most of these methods, however, involve solving Maxwell's equations in either integral or differential form. To do so, requires substantial computation on high-speed digital computers and, because of the time required, can be quite expensive.

One helpful approach to both the researcher and radiation safety officer has been the compilations of SAR provided in several editions of the Radiofrequency Radiation Dosimetry Handbook (2,9,10). With the Radiofrequency (RF) Handbook, the safety officer can measure the power density of incident RF or microwave fields in the workplace and then look up the predicted absorption rate for several human targets that vary in size from small children to adults. Even so, the human sizes available in the RF handbook are limited. To provide calculations of SAR, Durney (7) developed an empirical equation to be used with target shapes and sizes that were not available in the RF Handbook. Hurt and Lozano modified this equation and included their results in the 4th edition of the RF Handbook (2). Here, we describe and present (Appendix) a computer program written in the BASIC language that will solve Equation 5.10 from the Radiofrequency Radiation Dosimetry Handbook, 4th ed. (10), which allows the user to calculate SAR for any prolate spheroidal target on a personal desktop IBM-compatible computer.

PROGRAM SPECIFICS

The Radiofrequency Handbook (2) provides average SARs for several animal and human models, but it is limited to only a single or, in some cases, a few sizes of spheroids. For our behavioral studies at this command, we often estimate the average SAR of rhesus monkeys exposed to microwaves with values found in the Handbook. Dosimetry experiments are then conducted to more accurately estimate both average and local SAR in homogeneous models of the rhesus monkey and occasionally monkey carcasses. The Handbook, however, considers only one size of rhesus monkey. To extrapolate this information to other monkey sizes, we selected Equation 5.10 from the Radiofrequency Radiation Dosimetry Handbook, 4th ed. (2) and developed a BASIC language program to solve for average SAR.

$$SAR = \frac{A_1 f^2 / f_o^2 [1 + A_4 A_5 (f / f_o - 1)^2 (f / f_o)^B]}{1000 f^2 / f_o^2 + A_2 (f^2 / f_o^2 - 1)^2}$$

This equation is a modification by Hurt and Lozano (see 2) of the equation by Durney (7). Durney's equation was developed using a combination of antenna theory, circuit theory, and curve fitting to

solve for average SAR in the E polarization for spheroids of different sizes. Equation 5.10 was selected because it eliminates the inaccuracies produced by the step functions used by Durney (7) in the transition regions when SAR values are near f_{o1} and f_{o2} . Also, equation 5.10 specifically includes the frequency-dependent permittivity, which more accurately describes SAR-value variations created by the changes of epsilon (ϵ) with frequency.

The program (SAR.EXE) will run on a standard IBM personal computer or equivalent. It requires only 55 Kbytes of disk space to operate and is available on floppy disk from the authors. Menu selections allow the user to choose either a single frequency or an iteration of frequencies for which to calculate average SAR. Both selections permit the user to store the data in an ASCII file and to obtain a hard copy of the data.

Once the data are written to the ASCII file, graphical and statistical analysis can be performed. Sigma Plot 4.1 (11) was used to construct figures 1, 2, 3, and 4 using data obtained from the SAR.EXE program. Figure 1 compares the results from a 3-liter plastic bottle filled with a saline solution (0.9% Sodium Chloride Irrigation, USP) and a bag monkey model using the appropriate phantom muscle material (12) for the transmitted frequency (5.62 GHz) to the actual curve generated from the data obtained from the SAR.EXE program for the size of the bag monkey model being used. Figures 2, 3, and 4 replicate the graphs shown in the Radiofrequency Handbook (2) for an average man, medium rat, and medium mouse. The data points for graphs 2, 3, and 4 were obtained from the SAR program using the sizes given in the Dosimetry Handbook that corresponded to each subject.

EXPERIMENTAL RESULTS

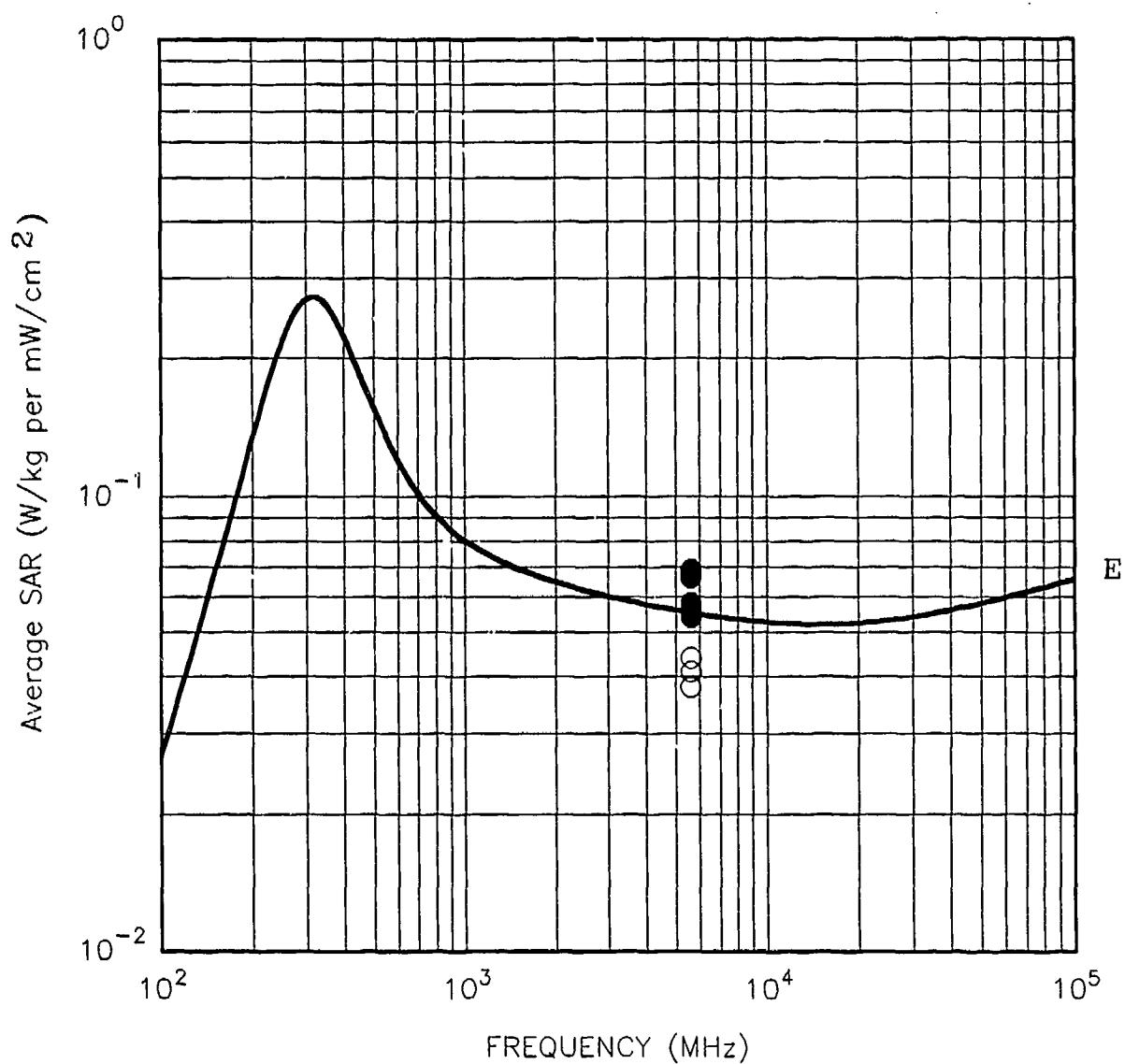
Pulsed microwave energy was generated by an AN/FPS-26A radar operating at 5.62 GHz. The average power output was adjusted to produce an average power density measurement of 108 mW/cm² in the far-field. To obtain data points for the 3-liter bottle and the bag monkey model, targets located in the far-field, and a sham placed away from the microwave field, were exposed for a period of 5-min. We constructed a twin-well calorimeter (13) to determine whole-body SAR after the primary design of Hunt and Philips (4). The absorption rate (W/kg) for each model was calculated using an integration of the calorimeter output (area under the curve using Simpson's Rule), model weight, specific heat rating, length of exposure, and area to length of exposure ratio of the twin-well calorimeter calibration. The SARs for the monkey bag model were determined experimentally using twin-well calorimetry and were compared to the SAR values calculated by the SAR-EXE program (0.053 W/kg) as shown in Fig 1.

PROGRAM ADVANTAGES

At this laboratory, the types of tissue simulating materials and the sizes of the models used to determine the SAR values can vary considerably from one model to the next. The primary advantage of the SAR.EXE program is that SARs for model sizes that are not available in the Radiofrequency Handbook can be quickly calculated. Whether SAR values are needed in the laboratory or in the workplace, they are calculated readily for a model of any dimension ranging from a small rat to a large human. A second advantage is that the program is stand-alone; it requires no other program or file to execute. It is a relatively small program and requires little space to operate (55 Kbytes) and can be run from either a floppy or hard disk. A third advantage is programming maintenance. The program is written in MicroSoft QuickBASIC Professional Development System version 7.1 (Appendix) allowing any changes to the program to be made by a qualified QuickBASIC computer programmer. The program is free of excessive code thereby keeping the BASIC program compact. The only disadvantage is a small sacrifice in accuracy of 10-15% of Equation 5.10, but this is offset by the advantage of calculating average SAR quickly without having to conduct extensive empirical experiments or solve Maxwell's equations on a mainframe computer.

CONCLUSIONS

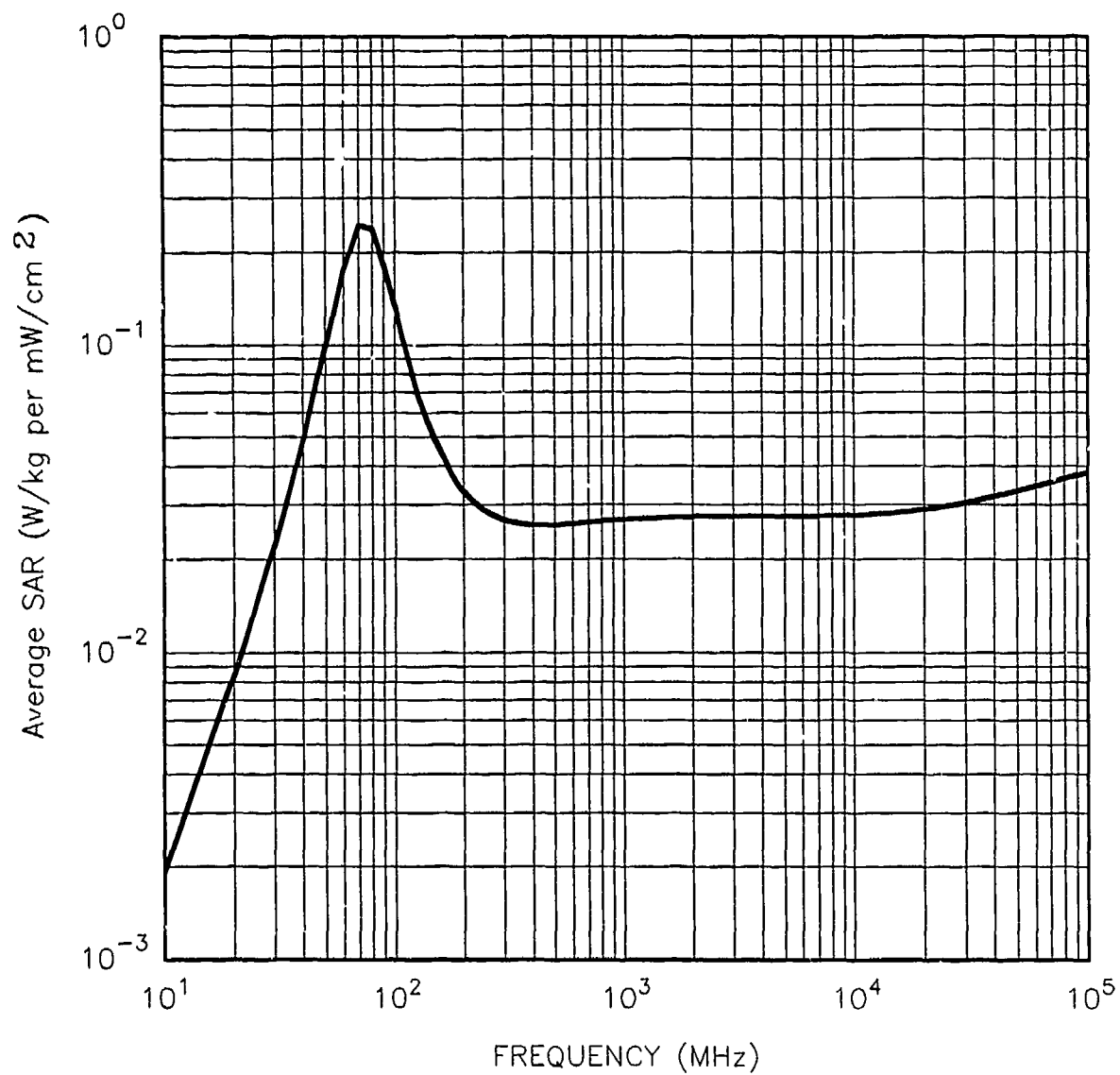
The empirical Equation 5.10 in the Radiofrequency Radiation Dosimetry Handbook is a relatively accurate method of calculating average SARs. A program to calculate SAR values for model sizes that are not found in the Radiofrequency Handbook is a useful tool for estimating these values quickly and with reliable accuracy conserving valuable time and money. We have utilized the SAR.EXE program at the Naval Aerospace Medical Research Laboratory and believe the addition of this program will be a beneficial aid for estimating SAR values in both laboratory and workplace environments.



Calculated plane wave average SAR in a prolate spheroidal model of a sitting rhesus monkey.

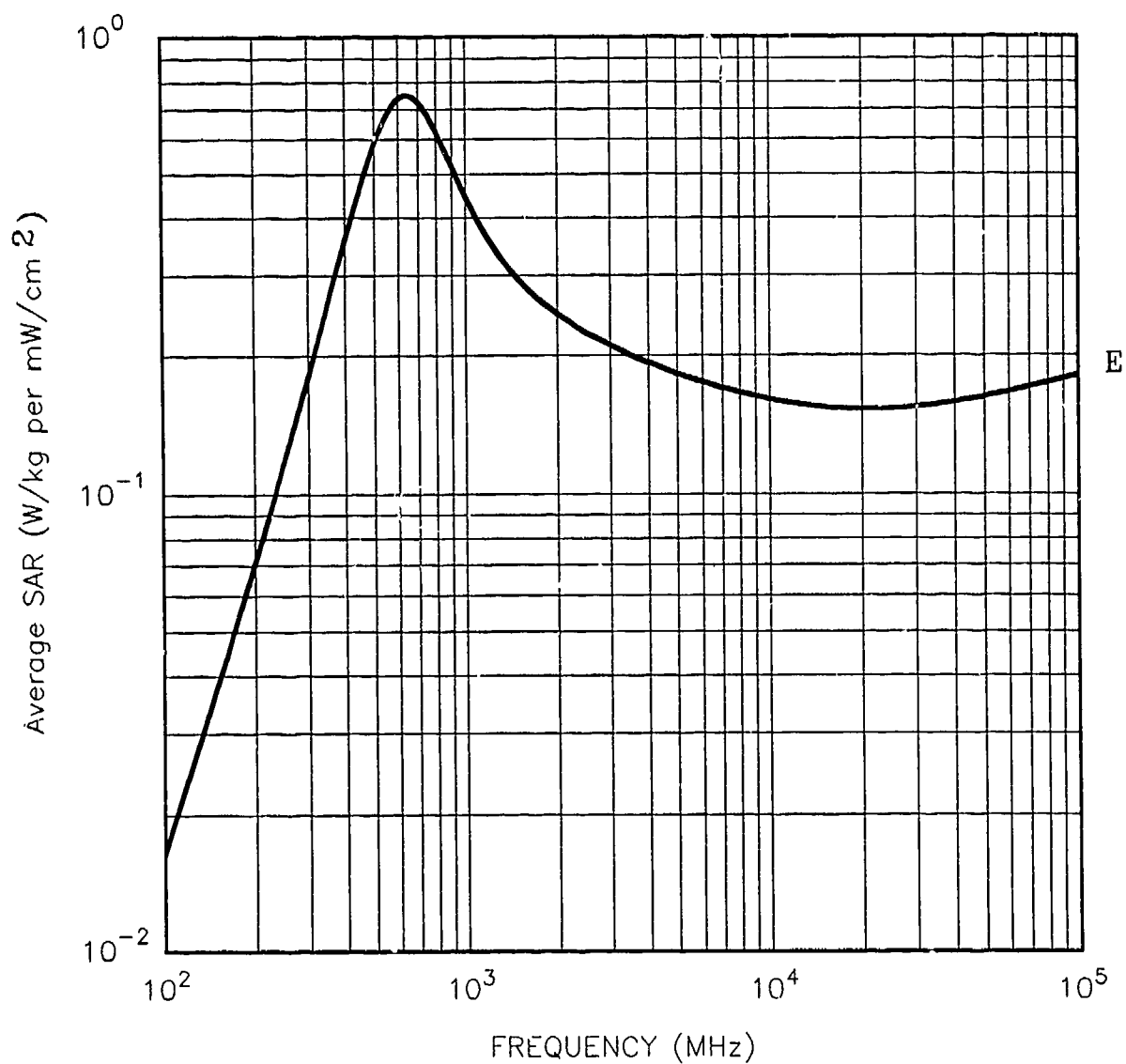
- Phantom muscle material in 5.2 kg monkey model
a = .23m, b = .067m
- 3 liter bottle filled with saline solution
a = .135m, b = .12m

Figure 1.



Calculated planewave average SAR in a prolate
spheroidal model of an average man.
 $a = 0.875\text{m}$, $b = 0.138\text{m}$

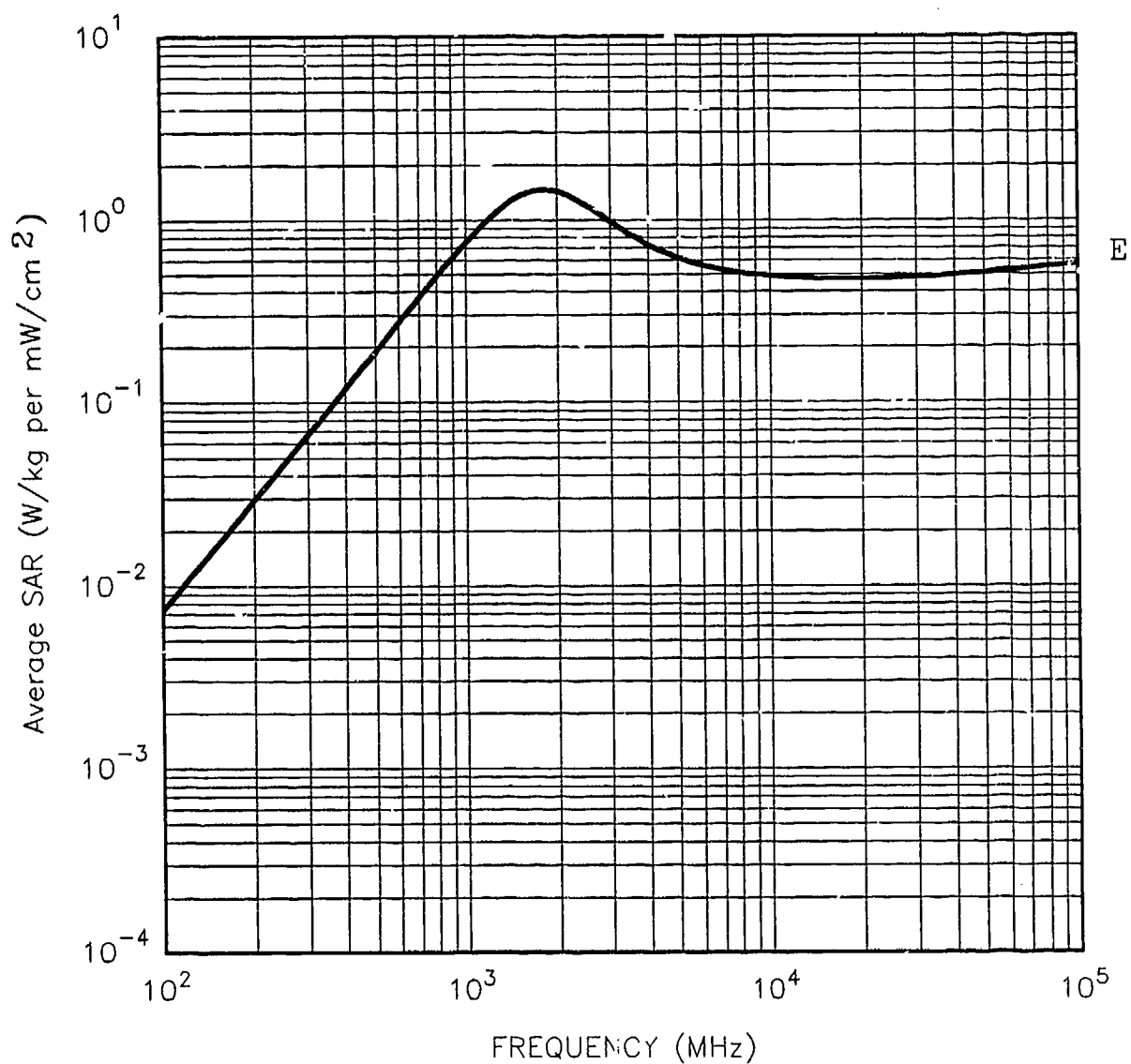
Figure 2.



Calculated planewave average SAR in a prolate
spheroidal model of a medium rat.

$$a = 0.1\text{m}, b = 0.0276\text{m}$$

Figure 3.



Calculated planewave average SAR in a prolate
spheroidal model of a medium mouse.

$$a = 0.035\text{m}, b = 0.0117\text{m}$$

Figure 4.

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Other Related NAMRL Publications

None are applicable.

APPENDIX

BASIC PROGRAMMING CODE FOR THE SAR.EXE PROGRAM

```

' SAR.BAS
' This program is written in MicroSoft QuickBasic Ver. 7.1

' Source Code by: Donald Hatcher and Dr. John D'Andrea
' Date: March 27, 1991

' This program calculates the SAR (W/Kg) for a given size
' target at a given frequency. If desired, the program will
' calculate the SAR's for a range of frequencies.
' Equation 5.10 on page 5.7 of the RadioFrequency Radiation Dosimetry
' Handbook is used to perform calculations.

DECLARE SUB Menu (selection)
DECLARE SUB TargetSize (a1, b1)
DECLARE SUB Frequency (f1)
DECLARE SUB PrintOptions (file$, printout$)

DECLARE FUNCTION ResonantFrequency1 (a1, b1, P1!, EX!)
DECLARE FUNCTION FrequencySquared1 (f1)
DECLARE FUNCTION ResonantFrequencySquared1 (FO1)
DECLARE FUNCTION Eq591 (EDPrime20!, EDPrimeF1, EPrimeF1, EPrime20!)
DECLARE FUNCTION Eq561 (a1, b1)
DECLARE FUNCTION Eq581 (a1, b1)
DECLARE FUNCTION Eq5101 (A1!, A2!, A4!, A5!, F2!, F02!, P1!, a1, b1, FO1, f1)
DECLARE FUNCTION Eq4241 (Conductivity!, P1!, f1)
DECLARE FUNCTION Eq4521 (f1)
DECLARE FUNCTION Eq4531 (f1)
DECLARE FUNCTION Eq551 (a1, b1)

CLS
CLEAR , , 4000
COLOR 15, 4

P1 = 3.14159264#
EX = 1 / 2
EX2 = 1 / 4

' The following values are for 20 GHz
EPrime20 = 27.8
EDPrime20 = 21.58
CONDUCTIVITY20 = 24
selection = 0

WHILE selection <> 3
CALL Menu(selection)
SELECT CASE (selection)
CASE 1
CALL PrintOptions(file$, printout$)
CALL Frequency(f)
interval = 1
CASE 2
CLS
CALL PrintOptions(file$, printout$)
PRINT
INPUT " Enter starting frequency (MHz)...: ", f
INPUT " Enter ending frequency (MHz)....: ", endf
INPUT " Enter frequency intervals (MHz).: ", interval
PRINT
endf = endf * 1000000
f = f * 1000000
CASE 3
GOSUB Quit
END SELECT

```

```

CALL TargetSize(a, b)

DO

    ' Calculate Resonant Frequency
    FO = ResonantFrequency(a, b, PI, EX)

    F2 = FrequencySquared(f)
    FO2 = ResonantFrequencySquared(FO)

    EPrimeF = Eq452(f)
    Conductivity = Eq453(f)
    EDPrimeF = Eq424(Conductivity, PI, f)

    A1 = Eq55(a, b)
    A2 = Eq56(a, b)
    A4 = Eq58(a, b)
    A5 = Eq59(EDPrime20, EDPrimeF, EPrimeF, EPrime20)

    SAR = Eq510(A1, A2, A4, A5, F2, FO2, PI, a, b, FO, f)

    PRINT
    PRINT USING " SAR = ##.#### for target sizes "; SAR;
    PRINT USING "of a = ##.#### and b = ##.####"; a; b;
    PRINT USING " at ##### MHz"; f / 1000000
    PRINT

    IF file$ <> "XXXXXXXX.XXX" THEN
        WRITE #1, f, SAR
    END IF

    IF UCASE$(printout$) = "Y" THEN
        LPRINT USING "#####          ##.####"; f / 1000000; SAR;
        LPRINT USING "          ##.####          ##.####"; a; b
    END IF

    f = f + interval * 1000000    ' Increment to next frequency

LOOP UNTIL f >= endf

PRINT
PRINT " Press Any Key To Continue...";
q$ = INPUT$(1)
selection = 0

WEND

Quit:
CLOSE
COLOR 7, 0
CLS
END

```

```

*****
FUNCTION Eq424 (Conductivity, PI, f) STATIC
    ' Calculate E'' (Double Prime) using formula 4.24 where :


$$\epsilon'' = \sigma / \omega \epsilon_0$$


    Eq424 = Conductivity / (2 * PI * f * 8.85E-12)

END FUNCTION
*****

```

FUNCTION Eq452 (f) STATIC

' The following calculations solve for e' using formula given on page 4.52

$$e' = \frac{2340000}{1+(f/78)^2} + \frac{62100}{1+(f/76 \times 10^3)^2} + \frac{1970}{1+(f/2.6 \times 10^6)^2} + \frac{30.8}{1+(f/340 \times 10^6)^2} + \frac{41.3}{1+(f/23 \times 10^9)^2} + 4.3$$

K = 2340000 / (1 + (f / 78) ^ 2) ' Calculate E' for frequency
H = 62100 / (1 + (f / 76000) ^ 2)
C = 1970 / (1 + (f / 2600000) ^ 2)
D = 30.8 / (1 + (f / 3.4E+08) ^ 2)
P = 41.3 / (1 + (f / 2.3E+10) ^ 2)
G = 4.3
Eq452 = K + H + C + D + P + G

END FUNCTION

FUNCTION Eq453 (f) STATIC

' Calculate Conductivity for frequency using formula given on page 4.53

$$\sigma = \frac{1.67 \times 10^{-6} f^2}{1+(f/78)^2} + \frac{4.54 \times 10^{-11} f^2}{1+(f/76 \times 10^3)^2} + \frac{4.21 \times 10^{-14} f^2}{1+(f/2.6 \times 10^6)^2} +$$

$$\frac{5.04 \times 10^{-18} f^2}{1+(f/340 \times 10^6)^2} + \frac{9.99 \times 10^{-20} f^2}{1+(f/23 \times 10^9)^2} + 0.106$$

K = ((1.67E-06) * f ^ 2) / (1 + (f / 78) ^ 2)
H = ((4.54E-11) * f ^ 2) / (1 + (f / 76000) ^ 2)
C = ((4.21E-14) * f ^ 2) / (1 + (f / 2600000) ^ 2)
D = ((5.04E-18) * f ^ 2) / (1 + (f / 3.4E+08) ^ 2)
P = ((9.99E-20) * f ^ 2) / (1 + (f / 2.3E+10) ^ 2)
G = .106

Eq453 = K + H + C + D + P + G

END FUNCTION

FUNCTION Eq510 (A1, A2, A4, A5, F2, F02, P1, a, b, F0, f) STATIC

' Solve for SAR using equation 5.10

$$SAR = \frac{A_1 F^2 / F_0^2 [1 + A_4 A_5 (F / F_0 - 1)^2 (F / F_0)^B]}{1000 F^2 / F_0^2 + A_2 (F^2 / F_0^2 - 1)^2}$$

```

AA = A1 * F2 / F02
MT = (4 / 3) * P1 * (a) * (b ^ 2)
UT1 = -.16
UT2 = (1.128 * (LOG(MT) / 2.302585) ^ 2)
UT3 = (.0438 * (LOG(MT) / 2.302585) ^ 4)
UT4 = (51.4 * b)
UT5 = (271 * b ^ 2)
UT6 = (8.902001 * a)
UT7 = (9 * a ^ 2)
UT = UT1 + UT2 - UT3 + UT4 - UT5 - UT6 + UT7
BX = F0 / f
BT# = UT ^ BX
BT# = BT# - 1

XX = 1 + (A4) * (A5) * (f / F0 - 1) ^ 2 * (f / F0) ^ BT#
EE = 1000 * F2 / F02
FF = A2 * ((F2 / F02 - 1) ^ 2)
JJ = EE + FF

Eq510 = AA * XX / JJ

```

END FUNCTION

FUNCTION Eq55 (a, b) STATIC

$$A_1 = -0.994 - 10.690a + 0.172a/b + 0.739a^{-1} + 5.660a/b^2$$

```

Eq55A = -.994 - (10.69 * a) + (.172 * (a / b))
Eq55B = (.739 * a ^ -1) + (5.66 * (a / b ^ 2))
Eq55 = Eq55A + Eq55B

```

END FUNCTION

FUNCTION Eq56 (a, b) STATIC

' Solve for A2 using equation 5.6

$$A_2 = -0.914 + 41.400a + 399.170a/b - 1.190a^{-1} - 2.141a/b^2$$

```

Eq56A = -.914 + (41.4 * a)
Eq56B = (399.17 * (a / b)) - (1.19 * (a ^ -1)) - (2.141 * (a / b ^ 2))
Eq56 = Eq56A + Eq56B

```

END FUNCTION

FUNCTION Eq58 (a, b) STATIC

' Solve for A4 using equation 5.8

$$A_4 = 0.335a + 0.075a/b - 0.804a^2 - 0.0075(a/b)^2 + 0.640a^3$$

Eq58A = (.335 * a)

Eq58B = (.075 * (a / b)) - (.804 * a ^ 2) - (.0075 * (a / b) ^ 2)

Eq58C = (.64 * a ^ 3)

Eq58 = Eq58A + Eq58B + Eq58C

END FUNCTION

FUNCTION Eq59 (EDPrime20, EDPrimeF, EPrimeF, EPrime20) STATIC

' Solve A5 using equation 5.9 on page 5.6

$$A_5 = |\epsilon / \epsilon_{20}|^{-1/4}$$

A51 = ABS(EDPrime20 * -(EDPrimeF));

A52 = EDPrime20 * EPrimeF

A53 = EPrime20 * -(EDPrimeF)

A54 = EPrime20 * EPrimeF

A56 = A54 + A51

A57 = A52 + A53

A58 = (EPrime20) ^ 2

A59 = (EDPrime20) ^ 2

A510 = A56 / (A58 + A59)

A511 = A57 / (A58 + A59)

A512 = A510 ^ 2

A513 = A511 ^ 2

Eq59 = (SQR(A512 + A513)) ^ -(1 / 4)

END FUNCTION

SUB Frequency (f) STATIC

PRINT

INPUT " Input desired frequency (MHz): ", f

f = f * 1000000

END SUB

FUNCTION FrequencySquared (f) STATIC

FrequencySquared = f ^ 2

END FUNCTION

SUB Menu (selection) STATIC

```

CLS
LOCATE 3, 26
PRINT "SAR Calculation Program"
LOCATE 5, 17: PRINT STRING$(40, 240)
LOCATE 7, 17
PRINT "1..... Single Frequency"
LOCATE 9, 17
PRINT "2..... Iterations of Frequencies"
LOCATE 11, 17
PRINT "3..... Exit SAR Program"
LOCATE 13, 17: PRINT STRING$(40, 240)
WHILE selection < 1 OR selection > 3
LOCATE 15, 26
PRINT "Make selection (1-3): "; : COLOR 31, 4: PRINT "■"
COLOR 15, 4
selection = VAL(INKEY$)
WEND

```

END SUB

SUB PrintOptions (file\$, printout\$) STATIC

```

CLS
PRINT
INPUT " Do you want to store data to a file (Y/N)....: ", response$
IF UCASE$(response$) = "Y" THEN
PRINT
INPUT " Enter file name: ", file$
OPEN file$ FOR OUTPUT AS #1
ELSE file$ = "XXXXXXXX.XXX"
END IF
PRINT
INPUT " Do you want to send output to printer (Y/N)...: ", printout$
IF UCASE$(printout$) = "Y" THEN
LPRINT
LPRINT " FREQUENCY (MHz)          SAR          TARGET  SIZES  "
LPRINT "                                a              b"
LPRINT "-----"
END IF
END SUB

```

FUNCTION ResonantFrequency (a, b, PI, EX) STATIC

$$f_o(Hz) = 2.75 \times 10^8 [8a^2 + \pi^2(a^2 + b^2)]^{-1/2}$$

$$\text{ResonantFrequency} = 2.75E+08 * ((8 * a ^ 2 + PI ^ 2 * (a ^ 2 + b ^ 2)) ^ -EX)$$

END FUNCTION

FUNCTION ResonantFrequencySquared (FO)

$$\text{ResonantFrequencySquared} = FO ^ 2$$

END FUNCTION

```
SUB TargetSize (a, b) STATIC
```

```
PRINT
PRINT " a = 1/2 the height of the target in meters."
PRINT " b = 1/2 the width of the target in meters (Less than .187)."
PRINT
a = 0
b = 0
bad = 0
DO
```

```
    LOCATE CSRLIN, 1: PRINT " Enter value for a:  "
    LOCATE CSRLIN - 1, 21: LINE INPUT "", a$
    bad = INSTR("/<>?~\';:[](-+_)(*&^%$#@|", a$)
    IF bad > 0 THEN a$ = "0"
    a = VAL(a$)
    LOCATE CSRLIN - 1, 1
    IF a <= 0 THEN
        LOCATE CSRLIN, 21: PRINT "**** Incorrect Entry ****"
        FOR repeat = 1 TO 3
            SOUND 1650, .2
            FOR delay = 1 TO 1000: NEXT delay
        NEXT repeat
        SLEEP 2
        LOCATE CSRLIN - 1
        LOCATE CSRLIN, 18: PRINT STRING$(30, 255)
        LOCATE CSRLIN - 1
    END IF
    LOOP UNTIL a > 0
```

```
PRINT
bad = 0
```

```
DO
```

```
    LOCATE CSRLIN, 1: PRINT " Enter value for b:  "
    LOCATE CSRLIN - 1, 21: LINE INPUT "", b$

    bad = INSTR("/<>?~\';:[](-+_)(*&^%$#@|", b$)
    IF bad > 0 THEN b$ = "0"

    b = VAL(b$)
    LOCATE CSRLIN - 1, 1
    IF b <= 0 OR b >= .187 THEN
        LOCATE CSRLIN, 21: PRINT "**** Incorrect Entry ****"
        FOR repeat = 1 TO 3
            SOUND 1650, .2
            FOR delay = 1 TO 1000: NEXT delay
        NEXT repeat
        SLEEP 2
        LOCATE CSRLIN - 1
        LOCATE CSRLIN, 18: PRINT STRING$(30, 255)
        LOCATE CSRLIN - 1
    END IF
    LOOP UNTIL b > 0 AND b < .187
```

```
PRINT
END SUB
```